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Fuzzy simulation of forest road surface parameters

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Annotation. The problem of construction of forest roads with the use of local low-strength substandard materials and industrial waste is considered. To solve the problem, the primary task is to develop a method for estimating the parameters of road surfaces taking into account the conditions of uncertainties in the data. This technique allows us to reasonably clarify some of the regulatory parameters and improve the technology of construction of forest roads, which was the goal of the work. To formalize the task, experimental studies were performed and on the basis of these results, the statement of the task of fuzzy derivation of the function for estimating the bearing capacity of the coating was performed. The synthesis of the output function is performed by means of Matlab.

1. Introduction

At present, the strategies adopted in various countries for the sustainable development of the world timber industry complex envisage a reassessment of the methods of functioning of their transport security system. The main research in this area is focused on improving the transport and operational qualities of forest roads and their construction. Much attention is paid to the study of processes occurring in the elements of road structures. As the analysis shows, road constructions made of high-quality road-building materials, treated with various binders, for example, asphalt concrete, cement concrete, reinforced soil, etc., are most often considered. As for forest roads, for a number of reasons, the above materials do not apply to them. The most affordable road-building materials for the construction of forest roads are only local non-conforming materials. These materials are either industrial waste or low-grade stone materials with unstable grain composition, unsuitable for the construction of public roads.

Forest roads not only provide a logging and timber transport system, but should also have a minimal negative impact on the ecological and environment-forming function of the forest. In turn, for sustainable forest management, this imposes certain restrictions on the choice of technical means and technologies for their construction.

It is also necessary to take into account the exceptional fire protection functions of forest roads. The complexity of the problem is evidenced by the current situation when, in world practice, both road construction and agriculture departments became involved in forest roads.

Thus, the implementation of the concept of sustainable forest management largely depends on the effectiveness of the construction and operation of forest road coverings from local low-grade, substandard materials. However, to date, the necessary methods of building such coatings are missing, mainly due to the presence of uncertainty conditions in the data on materials, which is a significant obstacle to solving the problem of sustainable forest management. In this regard, the creation of new, reliable methods for the construction of pavements of forest roads from substandard materials is a priority, which predetermined the purpose of this work.

The **aim** of the research was to improve the construction of forest roads using a new, scientifically based methodology for assessing the carrying capacity of road surface from substandard materials.

To achieve the goal tasks were set:

- experimentally assess changes in the physicomechanical properties of local stone materials under the influence of external loading;
- to study the processes of changing the carrying capacity of road pavement of forest roads, depending on the type of material, size and number of applied loading cycles;
- to develop a methodology based on a fuzzy model for assessing the carrying capacity of forest road cover, taking into account the conditions of uncertainty, which includes the following procedures:
  • performing a meaningful statement of the fuzzy inference problem;
  • definition of fuzzy membership functions in the problem based on the results experimental studies (fuzzification);
  • development of a base of rules for fuzzy products;
  • synthesis of a fuzzy model of the function of the dependence of the bearing capacity of the coating on the input parameters and the execution of the defuzzification using MATLAB application called Fuzzy Logic Toolbox;
- develop recommendations for improving the technology of paving forest roads from substandard materials.

1.1. Review of known studies

In domestic and foreign literature there are many publications devoted to the improvement of pavement structures. So in the world practice of functioning of logging systems under the scheme of sustainable forest management, built on the basis of the FSC criteria (compliance with the principles established by the Council on Forest Management) and ISO 14001, a special role is given to forest roads. As a result of the study of road structures, a large number of various recommendations for their construction and operation have appeared.

When designing and building, the peculiarities of forest roads are taken into account - low traffic intensity, limited speed limit and the use of rolling stock of forest trucks of the same type. This led to the fact that the choice of the type of forest roads moved into the area of a compromise between the intensity, the characteristics of the rolling stock, the bearing capacity of the road surface and the cost of their construction and operation.

Forest road surfaces are a discrete environment in which its constituent particles of low-grade materials are not interconnected or these connections are weak. Moreover, the creation of such discrete materials sustainable pavements is always fraught with difficulties. It is known that the absence of binding materials directly affects the basic physicomechanical parameters of the structural layers of road surfaces, in which the main factor will be only their structural strength. For such coatings, the methods for calculating their bearing capacity are developed only for cases when the coatings are made of certified materials.

Since in the modern practice of construction, operation and reconstruction of forest roads, local stone materials are used that have non-permanent grain composition and low strength, then a change in the wide-ranging physical and mechanical properties of such materials during the production of works is almost inevitable.

For a partial smoothing of this problem, a number of researchers began to divide construction materials into easily compacted and difficult to compacted [1, 2]. At the same time, the coherence, fragmentation of the material, its origin and the presence of structural bonds between its particles are not taken into account, which introduces uncertainty conditions in the design and choice of coating technology.

In general, world experience shows that at present there is no single computational mechanical model of a discrete medium made of stone materials, except for solutions for the frequent cases when an elastic body, a plastic body and some other cases are considered [3].

Since in discrete environments, the main interactions between its constituent particles are most often evaluated as a set of contacts between elements, the researchers try to idealize this environment.

For the case when a discrete medium appears to be non-ideal (elements of irregular geometric, non-spherical) shape, researchers consider it from other positions.

As follows from the results of the works considered, in computational models the number of contacts between the grains of the structural layer will increase with a decrease in the intergranular voidness of the material, but without taking into account the forces between the particles, which is a rather crude idealization.

To refine the model, a number of domestic researchers propose to evaluate the strength of a discrete layer only by the magnitude of the forces in the contacts at the particle boundary.

Other researchers propose to consider the magnitude of the side thrust in a discrete two-dimensional medium. In this case, the Hertz-Mindlin model (Hertz-Mindlin) is most often considered to evaluate normal and tangential stresses between particles.

In the considered models, it is assumed that discrete media will have strength, which depends not only on the size, shape of particles, but also on the characteristics of intergranular hollowness. However, the strength parameters taking into account these characteristics are not determined by the models.

To assess the effect of grain composition on intergranular hollowness, research by Fuller and Andreasen is most often used.

Taking into account the above, it can be assumed that, from the point of view of the characteristics of physical connections, the work of the pavement of automobile low-intensity roads will depend on the packing density, size and shape (cuboid, lamellar) of the material grains.

As for forest roads, low-grade stone materials have unstable grain compositions and are subject to significant grinding under the influence of compaction loads. The description of the process is further complicated by the fact that in such structures, small particles begin to play the role of not only the filler of voids in the frame, but with a certain mineralogical composition and degree of moisture can act as a cementing substance connecting larger particles [4]. And these conditions introduce an even greater degree of uncertainty in the problem, which requires an appropriate theoretical approach to solve it.

In addition to a review of the above studies of pavements, it should be noted that currently in almost any field of science the theory of fuzzy sets and its applications are widely used, in particular, fuzzy modeling, fuzzy logic, which allow formalizing problems with uncertainties.

In this paper, the solution of the problem, its specificity requires just such an approach. Both the initial data and the output parameters are characterized by uncertainty, which requires first their formalization, and then the formulation of the problem of fuzzy inference of the resulting function.

2. Methods and research

The present work included experimental and theoretical studies. The methodological base of experimental research is the theory of experiment and the methods of statistical data processing.

Experimental studies of pavements of forest roads from local low-grade substandard materials were carried out in two stages.

At the first stage, tests were carried out to change the physical and mechanical properties of the material under the influence of external loading. The experiments were carried out in laboratory conditions on a roller compactor, in accordance with the requirements of the main regulatory and technical documentation for the construction of roads.

The local stone material was used as the test object: limestone crushed stone (strength grade 400). With the analysis of changes in the grain composition of each fraction of stone material and intergranular hollowness, depending on the number and intensity of load cycles.

IOP Conf. Series: Earth and Environmental Science **316** (2019) 012026 doi:10.1088/1755-1315/316/1/012026

At the second stage, the model of compaction of stone materials in the pavements of forest roads was considered, and the processes of changing the bearing capacity of the coating depending on the type of material, size and number of applied load cycles were studied.

In the simulation, the relationship between the number of contacts and intergranular hollowness was used to estimate the mechanical interaction between its constituent particles:

$$C = C_0 + 9{,}7 \cdot (p_0 - p)^n , \tag{1}$$

Where, C – number of contacts between particles, C_0 – number of contacts at the initial stage of compaction; p_0 – intergranular hollowness at the initial stage of compaction; p – intergranular hollowness of compacted material; n – exponent.

The bearing capacity of the road cover will directly depend on the holding forces arising at the points of contact between the particles. In the case of application of an external impact on the coating, at the points of contact forces and holding force F arise, for a two-particle system, with an external pressure P will be equal to:

$$F = \frac{4\pi \cdot R^2 P}{C(1-\varphi)} , \tag{2}$$

where, P – pressure on the coating, MPa; R – particle radius, m; φ – intergranular voidness, %.

Since in the process of external influence, the radius of the particles in the grinding process is constantly changing, to be able to assess the contact forces between the particles, the change in the average value of the radius will be determined by the expression:

$$R_i = R_0 \cdot \frac{(f_i^{0-5} + f_i^{5-10} + f_i^{10-20})}{100} , \tag{3}$$

where, R_i – average particle radius at i-th cycle of exposure; R_0 – average particle radius before the construction process (compaction); f_i^{0-5} – the percentage of particles ranging in size from 0 to 5 mm; f_i^{5-10} – the percentage of particles ranging in size from 5 to 10 mm; f_i^{10-20} – the percentage of particles ranging in size from 10 to 20 mm.

As mentioned above, low-strength materials, due to their mineralogical composition, in some cases have the ability to self-monolith. This is due to the fact that, when reacting with water, the particles form hydration products and gradually harden.

Introducing the concept of an equivalent particle of stone dust, one can estimate the degree of its influence on the structural strength of the road surface. Thus, the equivalent particle of stone dust (ECHKP) is stone dust that reacts with water and forms a cemented accumulation of particles with increased strength and resistance to shear loads.

In this regard, the following assumptions were made when calculating the confining forces between particles: structural equivalent particles of stone dust are evenly distributed throughout the entire volume of the mixture formed during compaction; The generalized average particle radius is taken with regard to the formation of stone dust and is less than 0.25 mm in size.

In our case, to calculate the contact forces arising between particles of stone materials in the pavements of forest roads, the average calculated radius of the particle R_c was estimated by the formula

$$R_c = R_0 \cdot (1 - k_i) + \frac{R_i a_i}{100} , \tag{4}$$

where, k_i – grinding degree; a_i – the parameter of grouting, according to the formula

IOP Conf. Series: Earth and Environmental Science **316** (2019) 012026 doi:10.1088/1755-1315/316/1/012026

$$a_i = \frac{f_i^{0-0,25}}{100}, \tag{5}$$

where, $f_i^{0-0,25}$ – particle fraction <0.25 mm, %.

The data obtained form the basis of the mathematical model of coverage only from stable stone materials with conditioned grain composition that are not used in the construction of forest roads. Therefore, to expand the scope of the results, it is necessary to extend them to the description of the parameters of substandard materials, but taking into account the conditions of uncertainty. To this end, the third stage of research was conducted. His task was to obtain the dependence of the carrying capacity of coatings of non-conforming materials on the size of the fractional composition and the number of loading cycles during construction. To solve the problem taking into account the conditions of uncertainty, the methods of application of the theory of fuzzy sets of fuzzy logic were used. The fuzzy conclusion was carried out according to the Mamdani method [5]. For the practical implementation of fuzzy models, the computer mathematics system Matlab [6] was used, which has the means for this purpose - Fuzzy Logic Toolbox, FIS Editor applications. The sequence of actions was carried out in accordance with the research tasks listed above.

The statement of the problem in a meaningful form was carried out on the basis of the results of experimental studies and consisted in the qualitative description of the main dependences of the output value on the initial data.

In the fuzzification procedure, input and output variables in the form of fuzzy membership functions (linguistic variables) are justified, and subsets of linguistic variables are defined.

The size of the initial fractional composition of the stone material *K*, which varies in the range of 10-60 mm, is taken as the input value.

The second input value is the number of loading cycles, *NC*. The range of its change is from 10 to 50 loading cycles.

As the output value of the variable characterizing the carrying capacity of the coating, the value of the holding forces *F* between the particles of the stone material is taken. In the experiments it was established that these values can be in the range from 5.0 to 20.0 KN.

For linguistic variables, term sets are defined with the following values:

- «Holding forces, *F*» = {Min, Low, Moderate, High, Max};
- «Size of fractional composition, *K*» = {Min, Low, Moderate, High, Max};
- «Number of loading cycles, *NC*» = {Min, Low, Moderate, Low, Max}.

Graphically, the linguistic variables are shown in Figure 1.

In the linguistic variables, the values of the subsets are represented as triangular subsets, and at the edges of the universal set are taken the S-shaped and Z-shaped functions, similarly to [7]. Fuzzy functions were formalized in the Fuzzy Logic Toolbox [6] environment.

The fuzzy product rule base was formed by the following logical expressions:

- If *K* = Min and *NC* = Min, then *F* = Min;
- If *K* = Max and *NC* = Min, then *F* = High;
- If *K* = Max and *NC* = Max, then *F* = Max;
- If *K* = Moderate and *NC* = Low, then *F* = Low.

The fully developed rule base is shown in Table 1. A fragment of the fuzzy inference and defuzzification procedure in the Fuzzy Logic Toolbox environment is shown in Figure 2.

3. Results and discussions

As a result of the research, a picture was obtained of the change in the bearing capacity of the forest road surfaces, depending on the type of material, the size and number of applied loading cycles. Figure 3 shows the laboratory results of the grinding of low-strength limestone rubble brand 400, depending on the number of load application cycles.

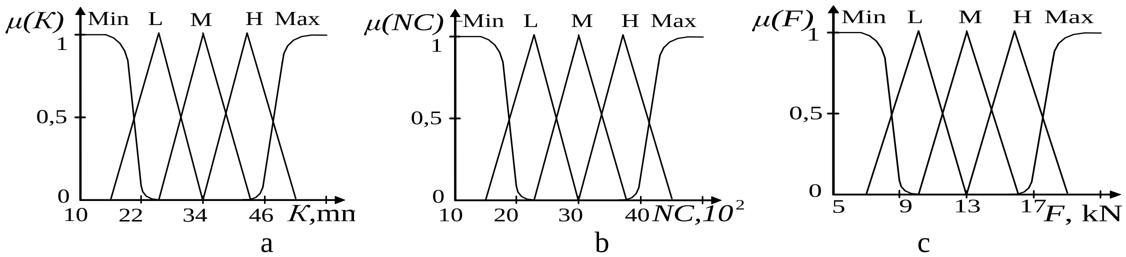

Figure 1. The proposed fuzzy membership functions: a - “Size of fractional composition, *K*”; b - “Number of loading cycles, *NC*”; c - “Holding forces, *F*”

Table 1. The fuzzy inference rule base, which simulates the magnitude of the holding forces between the particles of stone material *F=f(K, NC)*.

Values of the linguistic variable “Size of fractional composition *K*”	Values of output fuzzy subsets "Holding forces *F*" when changing the fuzzy function "Number of load cycles *NC*"				
	Min	**Low**	**Moderate**	**High**	**Max**
Min	Min	Low	Min	Min	Min
Low	Low	Moderate	Low	Min	Min
Moderate	Moderate	High	Moderate	Low	Min
High	Moderate	Max	High	Moderate	Low
Max	High	Max	High	Moderate	Low

It has been established that limestone low-grade crushed stone with a strength of 400 is much more susceptible to grinding under the effects of multiple cyclic loads than durable standard materials. As for the intergranular emptiness of a discrete layer, the influence of particles of a fraction less than 5 mm is especially strong there.

In the process of building and compacting the pavement, not only is the grinding of particles, but also a decrease in pressure between the grains of stone material until the moment when the increase in the number of contacts slows down and a redistribution of forces between the particles occurs. The subsequent compaction leads to an increase in the holding forces between the grains, reaching the greatest bearing capacity of the road surface. However, after reaching these values, under the influence of external influence from automobiles, there will be a consistent decrease in the holding forces in the coatings (Figure 4). This fact is confirmed by the experience of operating both forest roads [8, 9, 10] and public roads.

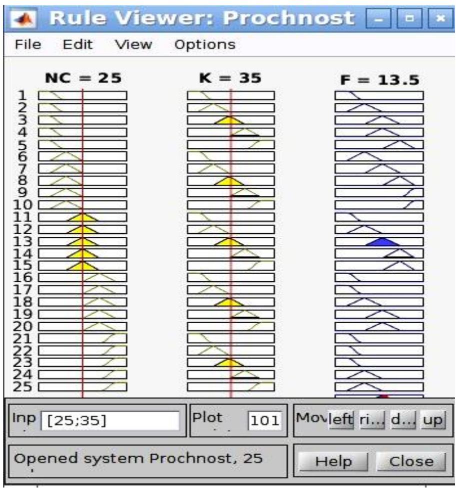

Figure 2. Fragment of a fuzzy inference procedure in Fuzzy Logic Toolbox.

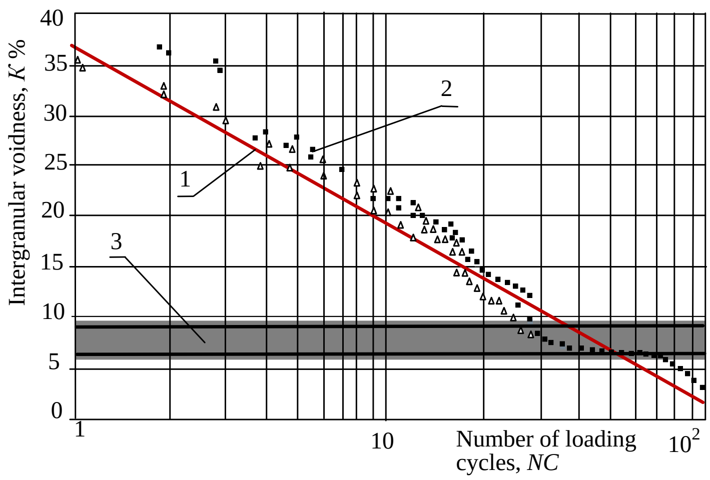

Figure 3. Intergranular voidness dependingon the number of loading cycles: 1 – experimental;2 – theoretical; 3– zone of highest density.

As can be seen from the graphs in Fig. 4, the change in the holding forces F occurs differently in different ranges of the number x of loading cycles. So in the range from 0 to 20 cycles, active packing of particles with partial grinding occurs, it is described by a polynomial of the 2nd degree Y=21, 295 x^2 – 257,47x+1532,9. This range is characterized by the greatest structural strength of the coating. In the range from 20 to 100 cycles, further grinding of the stone material occurs and it is described by a power function of the form Y=4905,5 $x^{-0,614}$. In this range, due to the formation of stone fines, cementing bonds begin to form actively. In the range from 100 to 1000 cycles, an area with a stable structural strength of the coating is formed, which is described by a function of the form Y= 12785 $x^{-0,831}$. In the range from 1000 to 1000000 cycles, it is a function of the form Y= 5E +6$x^{-1,687}$ and is the area where the structural strength of the forest road cover weakens.

It was revealed that in the process of compaction of local low-strength stone materials, in addition to grinding material particles, an increase from 5 to 30% of the holding forces between the particles can occur due to the occurrence of cementation.

To assess the restraining effort that most accurately describes the bearing capacity of the coating, the corresponding function was obtained by the above method. The graph of the function $F=f(K, NC)$ depending on the size of the fractional composition and the number of loading cycles is shown in Figure 5.

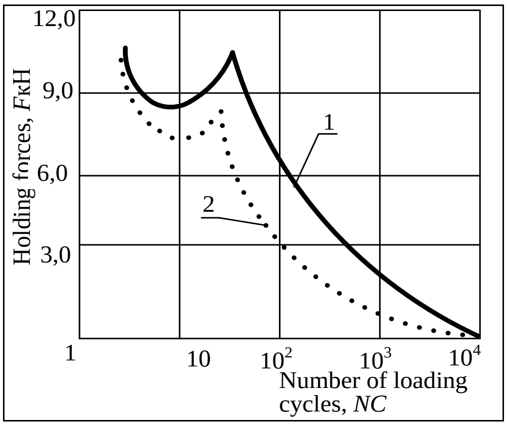

Figure 4. Changes in holding forces between particles in the cover of forest roads by the number of load cycles. 1– conforming material; 2– substandard material.

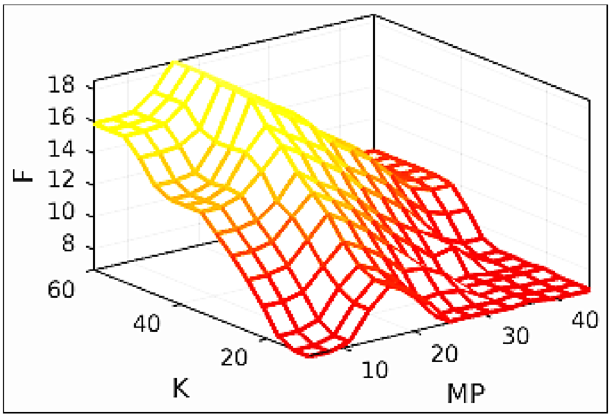

Figure 5. Graph of the fuzzy output function $F=f(K, NC)$.

4. Conclusion

The paper studied the patterns of compaction of local stone materials in the construction of forest roads and developed a methodology for assessing the bearing capacity of road surfaces from substandard materials.

Using the proposed methodology, recommendations were developed for improving the technology of building forest roads and proposals for adjusting standards for assessing the bearing capacity of a road surface made of non-conforming materials. The following main provisions were taken into account.

1. The obtained data reveal a general tendency, which consists in the phasing of a change in the holding forces arising during compaction of a granular material.

2. The developed fuzzy model shows sufficient adequacy when compared with experimental data and allows implementing a fundamentally new approach to solving the considered problem, taking into account the uncertainties in the initial data.

3. The functional dependence of the magnitude of the confining forces between the particles to estimate the bearing capacity of the coating, obtained on the basis of a fuzzy inference, indicates those regulatory process parameters that require revision.

4. Since the achievement of the greatest strength of coatings occurs with a decrease in the number of loading cycles, it is permissible not to compact the material during construction. In practice, this means a reduction in the number of sealing aisles in one trace less than the standard value. The subsequent compaction is foreseen by the machines in the future construction or transport during operation. Previously, some authors have expressed such an assumption, but without the necessary justification.

5. The results of the research show that in order to improve the quality of pavements made of unfortified low-strength stone materials, it is advisable to add particles of smaller fractions to their composition to reduce the degree of grinding, as well as pulverized materials that have cementing properties.

6. The process of grinding stone substandard materials is accompanied by significant changes in the grain composition. It is shown that to assess the basic physicomechanical properties, it is advisable to use intergranular hollowness as the main indicator of grinding.

7. For the first time it is substantiated that during the construction of forest roads from local substandard stone materials to achieve the required standard indicators, the number of passes of a vibratory roller in one track should be in the range of 6 to 8, which corresponds to 20 ... 30 load application cycles.

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